

Wide-bandwidth acoustical characterization of anchovy and sardine from reverberation measurements in an echoic tank

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The total-scattering cross-sections (σ_t) of anchovy (*Engraulis mordax*) and sardine (*Sardinops sagax caerulea*) were measured acoustically over a wide bandwidth (0.5–202 kHz) from ensembles of reverberation time-series. Measurements were made sequentially in two cylindrical, galvanized-steel tanks containing filtered seawater ($21 \pm 1^\circ\text{C}$). The lower-frequency measurements were made from two groups of fish (35 anchovy and 10 sardine) in a 1000-l tank, and those at higher-frequency (≥ 36 kHz) from 10 individual fish in a 100-l tank for each species. Thus, wide-bandwidth, total target strengths ($\text{TTS} = 10 \log_{10}(\sigma_t/4\pi)$) were estimated for multiple sizes of these important pelagic species of the California Current. The TTS frequency dependence ($\text{TTS}(f)$) is significantly different for these two species. For sardine, it first increases and then decreases over the frequency range, whereas for anchovy it increases monotonically with frequency. Moreover, at 38, 70, 120, and 200 kHz the variations of TTS with fish length and weight were markedly non-linear. Empirical estimates of TTS were statistically compared with theoretical predictions derived using the Kirchhoff ray-mode model. When surveying with echo-integration methods these measurements should be useful in the acoustical identification and classification of anchovy and sardine and for estimating their sizes.

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Keywords: echo-trace classification, Kirchhoff ray-mode model, swimbladder, total cross-section, total target strength.

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Introduction

Anchovy and sardine are key species of many coastal environs such as the California Current ecosystem and are the target of many fisheries worldwide. Both ecological investigations and fisheries-management efforts require accurate information about their dispersion and abundance over large scales of space and time. Current survey strategies involve a variety of methods ranging from the net capture of adults (Mais, 1974) and sonar mapping (Hewitt *et al.*, 1976), to pumping and sorting their eggs (Hunter and Lo, 1997).

Echo-integration survey techniques (EI; Ehrenberg and Lytle, 1972) are potentially the most effective means of surveying these important fish species. However, the accuracy of EI estimates of fish dispersion and abundance can be compromised significantly by uncertainties associated with species identification and backscattering cross-section (σ_{bs}) or target strength ($\text{TS} = 10 \log_{10}(\sigma_{bs})$; Demer

et al., 1999). Many techniques have been developed to identify and classify species that are represented within an echogram. With varying degrees of success, the methods have traditionally employed discriminators based on single-frequency observations of animal behaviour, aggregation density, size, shape and location, and acoustical-volume backscattering and target strengths (see Horne, 2000). Frequently, however, the effectiveness of these methods relies heavily on the experience of the echogram interpreter.

More accuracy and objectivity is offered by methods that exploit the differences in backscattered energy at two or more frequencies (e.g. Madureira *et al.*, 1993). However, in ecosystems with high species diversity, even more information is required to identify and classify species effectively (e.g. Greenlaw and Johnson, 1983). Towards this end, wide-bandwidth methods are most promising (Martin *et al.*, 1996). Notwithstanding their potential, the wide-bandwidth techniques ultimately require spectral

characterization of target species and all the potentially coexistent scatterers.

Recently, a new method was proposed that conveniently allows wide-bandwidth measurements of total cross-section (σ_t) or total target strength ($TTS = 10 \log_{10}(\sigma_t/4\pi)$) of fish to be made in an echoic tank (De Rosny and Roux, 2001). In the method, numerous acoustic pulses are transmitted into the tank and the reverberated field $h_k(t)$ is recorded. If the cavity contains one or more scatterers in motion from pulse-to-pulse, the reverberant field is composed of echoes from the boundaries of the cavity and echoes from the moving scatterers. For a single pulse, the two parts cannot be separated. However, if the positions of the transmitter and the receiver are fixed from pulse-to-pulse, then the echoes due to the boundaries are correlated, whereas the echoes from the moving scatterers are not. Therefore, the coherent and incoherent intensities in the cavity can be estimated for numerous pulses transmitted in it, and the scattering-mean free path (l) can be estimated from the slope of the coherent intensity divided by the incoherent intensity. The scattering-mean free path (l) depends on the number of scatterers (N), the total-scattering cross-section (σ_t), the volume of the cavity (V), and the sound speed (c). Thus, TTS is determined by l if the other three parameters are known. The accuracy and precision of this method for estimating TTS was demonstrated to be at least 0.4 and ± 0.7 dB, respectively (Demer *et al.*, 2003).

The aims of this study were first to use this technique to measure TTS of live anchovy (*Engraulis mordax*) and sardine (*Sardinops sagax caerulea*) over a wide bandwidth and for multiple fish sizes, second to compare the results within and between species, and third to compare the results with the theoretical predictions of the Kirchhoff ray-mode model (KRM; Clay and Horne, 1994; Medwin and Clay, 1998; Jech and Horne, 2002). These measurements should be useful in the acoustical identification and size estimations of anchovy and sardine, thus improving survey results when using EI methods.

Methods

From December 2001 through mid-January 2002, the first measurements of TTS of anchovy and sardine were made over a wide bandwidth (0.5–202 kHz), in the Advanced Survey Technologies Laboratory of the Southwest Fisheries Science Center (SWFSC). Following the method of De Rosny and Roux (2001), and procedures described by Demer *et al.* (in press), the mean TTS was estimated from an ensemble of pulse-echo recordings made in a reverberant cavity containing one or more animals in motion.

The cavity was one of two cylindrical, galvanized, and corrugated steel tanks (Figure 1) (1.6 m diameter by 0.6 m high and 1000 l; and 0.5 m diameter by 1 m high and 100 l) containing seawater at a temperature of $21 \pm 1^\circ\text{C}$. In the large tank, the experiment was conducted at centre

frequencies (f_c) ranging from 0.5 to 34 kHz, with 0.5 kHz steps. Frequency-modulated 2 ms pulses with 1 kHz bandwidth were transmitted two times per second using an omnidirectional broad-bandwidth transmitter and received bi-statically with an omnidirectional broad-bandwidth receiver. The reverberation time-series ($h_k(t)$) was recorded for each pulse by digitizing the received sound pressure levels at 100 kHz using a 12-bit analogue-to-digital converter. Groups of 35 anchovy and 10 sardine were investigated, each species independently, over the whole frequency range. However, for frequencies below about 7 kHz, the number of modes excited in the cavity may not be sufficient to obtain a homogeneous sound field (Demer *et al.*, 2003) and so the accuracy of the measurements from 0.5 to 7 kHz is thought to be questionable.

In the small tank, the experiment was conducted at f_c from 36 to 202 kHz, with 2 kHz steps. Frequency-modulated 500 μs pulses with 2 kHz bandwidth were transmitted two times per second using an omnidirectional broad-bandwidth transmitter and received bi-statically with two omnidirectional broad-bandwidth receivers. The $h_k(t)$ were recorded for each pulse by digitizing the received sound pressure levels at 450 kHz using a 12-bit analogue-to-digital converter. In this tank, the measurements were obtained from 10 individual fish for each species.

Using 200-record ensembles at each f_c , the slope of the average cross-correlation ($S_c(t)$) divided by the average intensity ($S_i(t)$) provided estimates of l and hence TTS:

$$S_c(t) = \frac{1}{N} \sum_{k=1}^N h_k(t) h_{k+1}(t) \quad (5)$$

$$S_i(t) = \frac{1}{N} \sum_{k=1}^N h_k^2(t) \quad (5)$$

$$S(t) = \left\langle \frac{S_c(t)}{S_i(t)} \right\rangle. \quad (5)$$

As shown by De Rosny and Roux (2001), if $t \ll l/c$, then $S(t) \approx \exp(-tc/l)$, and:

$$\sigma_t = \frac{1}{nl} \quad (5)$$

$$n = \frac{N_{\text{scatterers}}}{V_{\text{cavity}}}. \quad (5)$$

Estimating the exponential decay of the ratio $S(t)$ provides the estimate of σ_t (or TTS).

At each f_c , the TTS measured from the groups of fish were normalized to mean single-fish-TTS. These experimental TTS were also reduced, or normalized to a 1-m long fish (TTS_{re}):

$$TTS_{re} = TTS - 20 \log_{10} \left(\frac{L}{1 \text{ m}} \right). \quad (5)$$

For comparison, theoretical TTS were calculated for each species using the KRM. The values for the compressibility (ρ) and the sound speed (c) for the fish flesh and

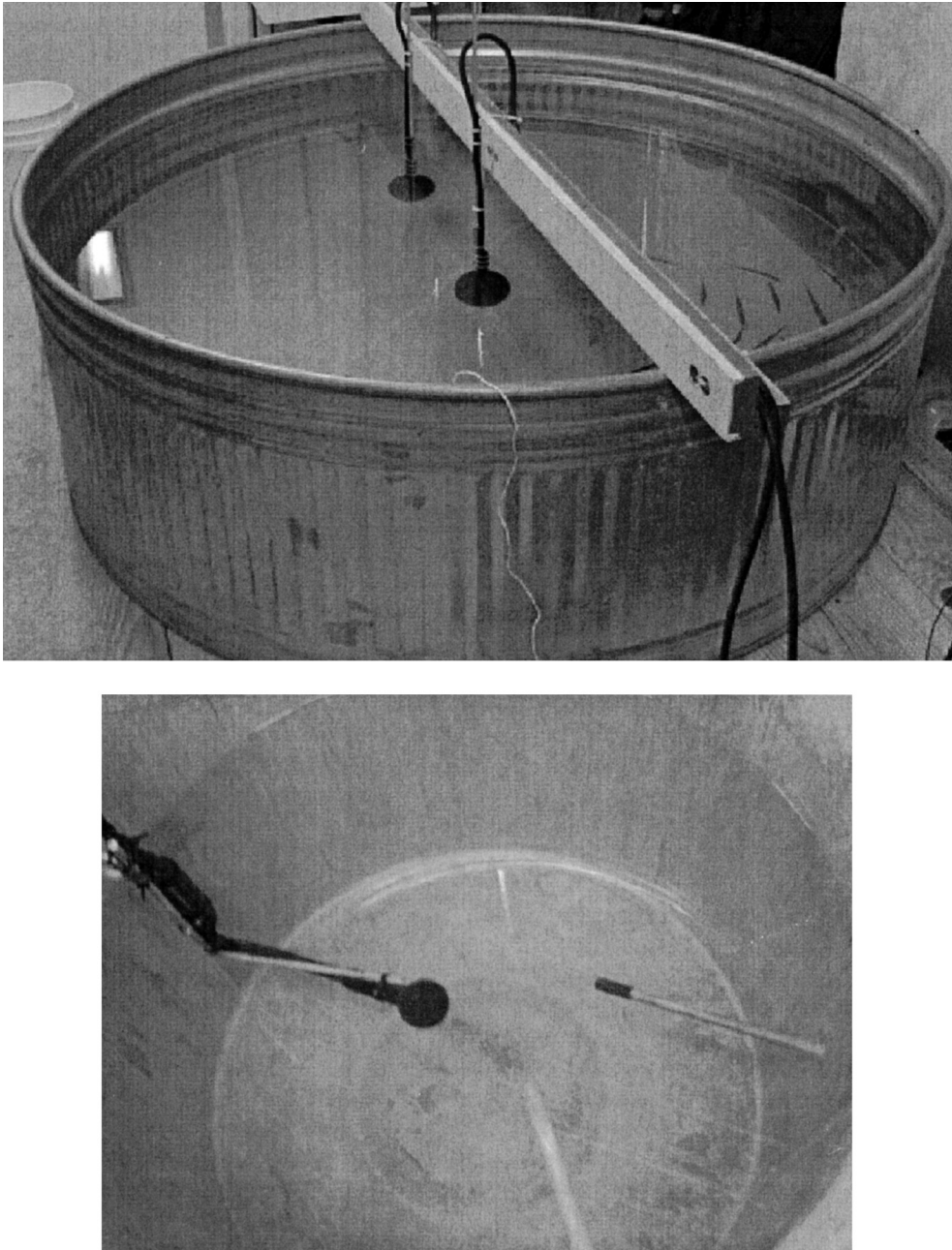


Figure 1. Cylindrical, galvanized, and corrugated steel tanks of capacity 1000 and 100 l.

for the swimbladder (Table 1) were adopted from Clay and Horne (1994) and Medwin and Clay (1998). To characterize the other KRM parameters, total lengths (L) of each fish were measured to the nearest millimetre (Figures 2 and 3), and X-radiographs were taken to estimate the shape and size of a generic swimbladder for each species and length (Figure 4). Fish weights were also measured to the nearest gram. The KRM model is only valid for

Table 1. The physical properties of fish flesh and swimbladder from Clay and Horne (1994) and Medwin and Clay (1998).

Medium/subscript	ρ kg/m ³	c m/s	$g = \rho_2/\rho_1$	$h = c_2/c_1$
Ambient water/ _A	1030	1490	—	—
Fish flesh/ _{bod}	1070	1570	1.04	1.05
Swimbladder/ _{blad}	1.24	345	0.001	0.22

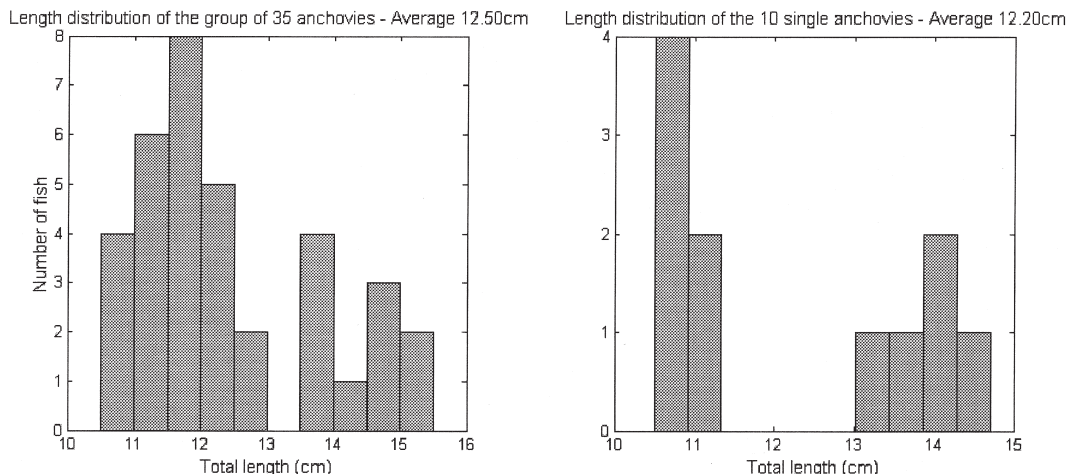


Figure 2. The length distribution of the anchovy.

$ka > 0.15$ (Foote, 1985; Medwin and Clay, 1998), where a is the equivalent cylindrical radius of the swimbladder of the fish. For the shapes of the anchovy and sardine in this experiment, the equivalent cylindrical radii of the swimbladder are 4 and 6 mm, respectively. The KRM model is therefore valid above the minimum frequencies of approximately 9 and 6 kHz, respectively.

The shapes of the fish were easily determined from the X-radiographs, but determination of the swimbladder characteristics was more ambiguous. This was because while the swimbladder cavities were discernible, their actual shapes and sizes depend on many non-controlled physiological and environmental parameters (O'Connell, 1956). As the fish in these experiments were acclimated to very shallow water, it was assumed that the swimbladders were fully inflated and their dimensions could be estimated from that of the cavities. Dimensions and shapes compared

favourably to those in the more extensive investigations of O'Connell (1956) and Blaxter and Hunter (1982). The swimbladder for the sardine was modelled as a single elongated chamber, whereas that for the anchovy was modelled as a double chamber (Figure 4).

Using these parameters and the KRM, theoretical TTS were calculated by integrating the field scattered by the body and swimbladder of the fish in all directions, and averaged for all possible incidence angles. The computed functions $TTS(f_c)$ and $TTS_{re}(kL)$, where $k = 2\pi f_c/c$, are shown for each species in Figures 5 and 6.

Results

Because the length distributions for the fish measured individually are not exactly the same as for the fish measured in groups (Figures 2 and 3), the TTS measurements

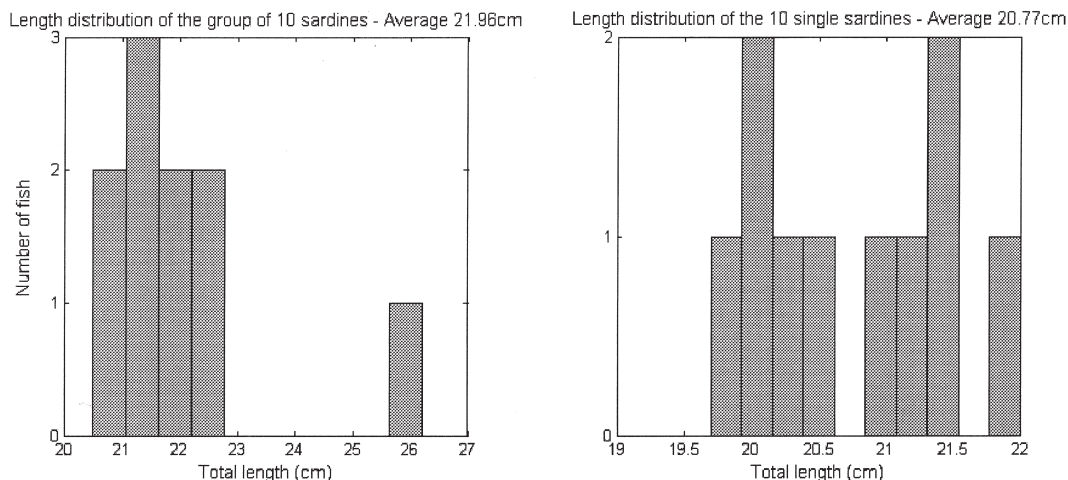


Figure 3. The length distribution of the sardine.

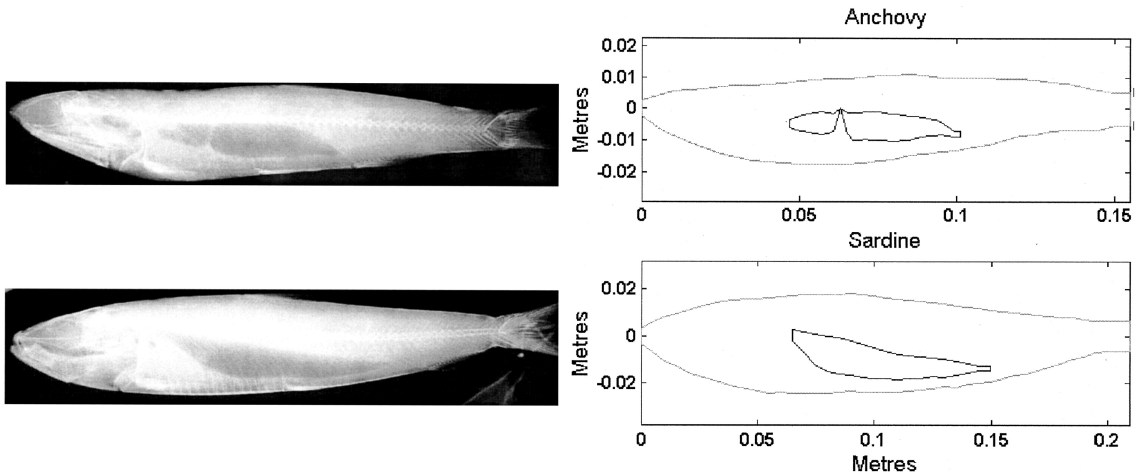


Figure 4. X-radiographs of an anchovy (top left) and a sardine (bottom left) and the shape of the body and the swimbladder of the generic anchovy (top right) and sardine (bottom right).

obtained in the two tanks exhibit slight offsets between 34 and 36 kHz (Figures 5 and 6). It is also apparent that TTS_{re} does not effectively normalize for L in every case. This is probably the result of a non-linear relationship between the swimbladder σ_t and L^2 caused by the large variation in swimbladder shape and size with fish length (O'Connell, 1956; Blaxter and Hunter, 1982). Moreover, the length distributions for the individually measured fish are about 10% wide and do not provide a broad distribution of length.

Considering the results in the frequency domain (Figure 7), there are marked differences between the average TTS of the two species. The $TTS(f_c)$ for the anchovy monotonically increases from 0.5 to 202 kHz and has a mean of -44 dB ($\sigma_t \approx 5$ cm²). In contrast, the $TTS(f_c)$ for the sardine decreases with increasing frequency from approx-

imately 100 to 202 kHz and has a mean of -39 dB ($\sigma_t \approx 16$ cm²). The ratio of mean σ_t for the sardine and the anchovy is 3.2. The square of the ratio of average lengths for the 10 sardine and anchovy is about 2.9 ((20.8 cm/12.2 cm)²). These ratios should be similar if σ_t is proportional to L^2 . However, at $f_c = 38, 70, 120$, and 200 kHz, there is no clear relationship between TTS and length or weight for either species (Figures 8 and 9). This discrepancy may be an artefact of the small ranges of L and the discrete frequencies considered, or it may be caused by non-symmetric changes of swimbladder size with fish length.

For anchovy, the mean TTS measurements are close to the KRM predictions (Figure 7). For frequencies from 36 to 202 kHz, the measurements match the theoretical predictions to better than 1 dB. Also, from 7 to 36 kHz, the TTS

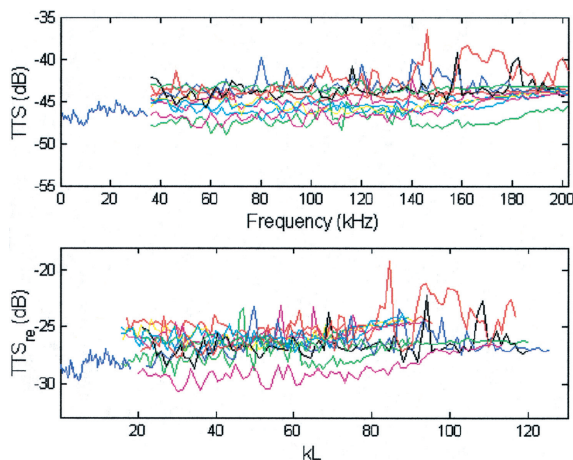


Figure 5. Total target-strength (TTS) measurements for the anchovy in the frequency domain (top) and kL domain (bottom). The results are for 10 individual fish at $f > 36$ kHz and the average of 35 fish at $f < 36$ kHz.

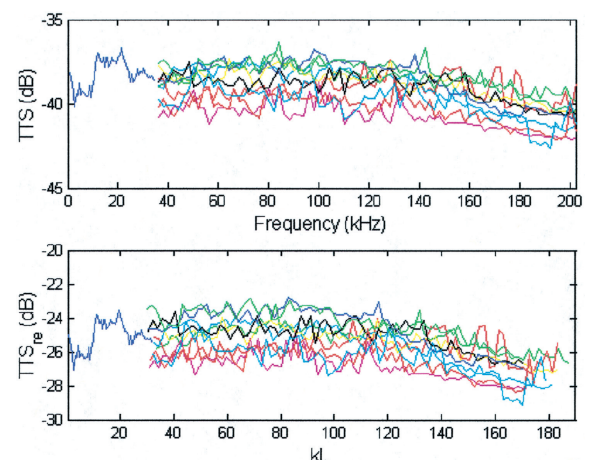


Figure 6. Total target-strength (TTS) measurements for the sardine in the frequency domain (top) and kL domain (bottom). The results are for 10 individual fish at $f > 36$ kHz and the average of 10 fish at $f < 36$ kHz.

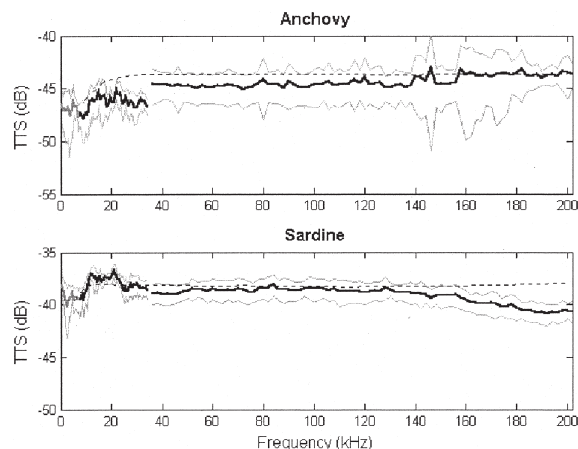


Figure 7. The average TTS measurements (dark solid line) ± 1 s.d. (light solid lines) for anchovy and sardine. The dashed lines are KRM theoretical predictions of the TTS for one anchovy and one sardine. The measurements below 5 and 7 kHz (grey) for the sardine and anchovy, respectively, are dubious because of the low number of modes excited in the cavity (see "Methods" section for elaboration).

measurements differ from the theoretical predictions by less than 2 dB. Note however, that the differences between the measurements and the theoretical predictions appear to be systematic rather than random.

For sardine, the mean TTS also compares reasonably well with the KRM predictions (Figure 7). It is noteworthy, however, that for frequencies from 140 to 202 kHz the discrepancies between the modelled and measured TTS increase with frequency. In this case, the theoretical predictions are relatively constant, while the mean TTS measurements decrease as f_c^3 . If this decrease in TTS were the result of sound absorption by the fish, an f_c^2 relationship would be expected. Further research is needed to explain this observation.

For the wide-frequency band from 25 to 140 kHz, the discrepancy between the theoretical predictions and the experimental TTS for sardine is less than 0.5 dB. Between 7 and 25 kHz, the differences are only about 1 dB. In this case, though, the TTS spectra exhibit a plateau between 10 and 25 kHz. Approximating the sardine swimbladders as prolate spheroids of air in seawater at 1 atm, the resonance frequencies should be between 200 Hz and 1.2 kHz (Weston, 1967). Therefore, this feature should not be caused by swimbladder resonance. The TTS(f) for anchovy does not have a similar plateau in this same frequency range, but the spectra for both species flattens at the lowest frequencies. To illustrate this point, the TTS is plotted between 0.5 and 36 kHz (Figure 10). While the TTS for the 35 anchovy and the 10 sardine, each normalized to one fish, are about 3 dB different, the plateau is evident in the sardine spectra but not in the anchovy spectra. Again, at the

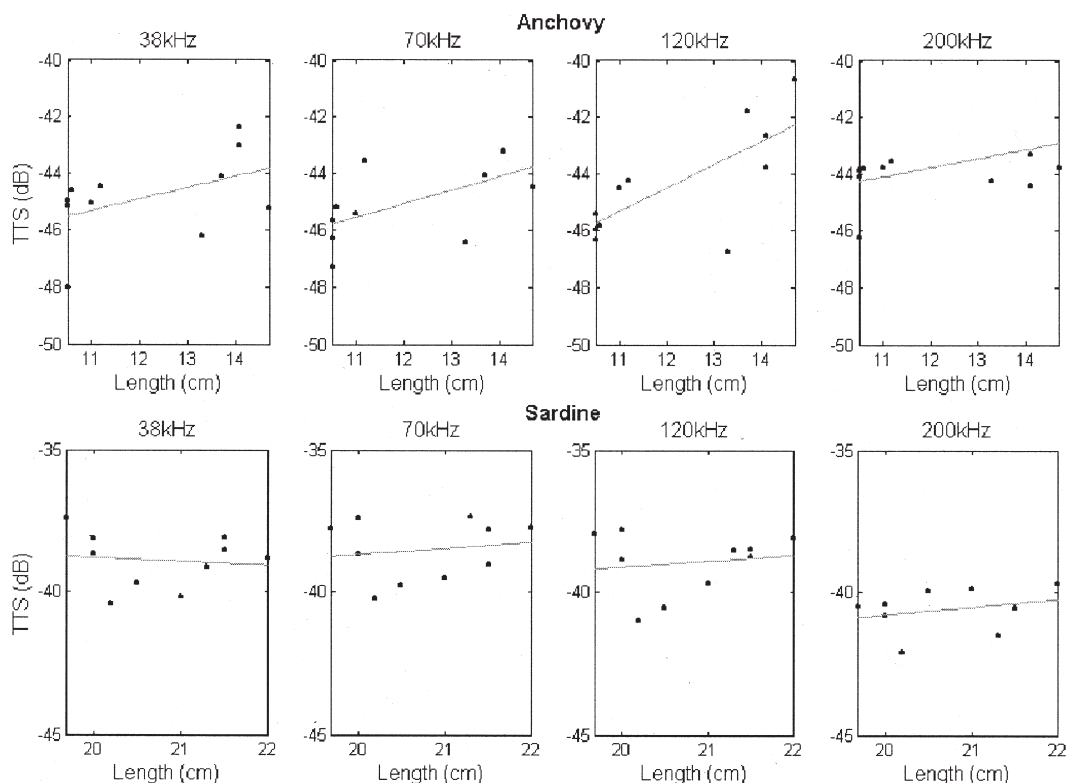


Figure 8. TTS versus fish length at $f_c = 38, 70, 120$, and 200 kHz for anchovy (top) and sardine (bottom).

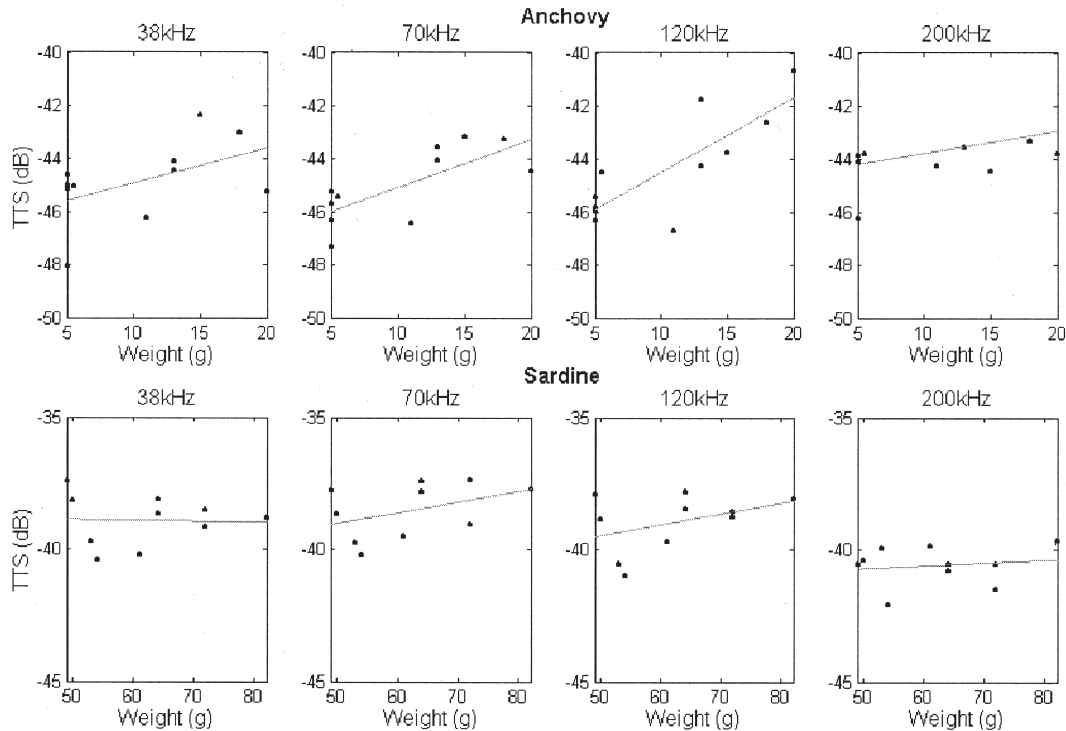


Figure 9. TTS versus fish weight at $f_c = 38, 70, 120, 200$ kHz for anchovy (top) and sardine (bottom).

lowest frequencies, the TTS measurements for sardine exhibit the same flattening as observed for the anchovy. This flattening of both spectra below 7 kHz is probably due to the low number of modes excited in the cavity in this frequency band.

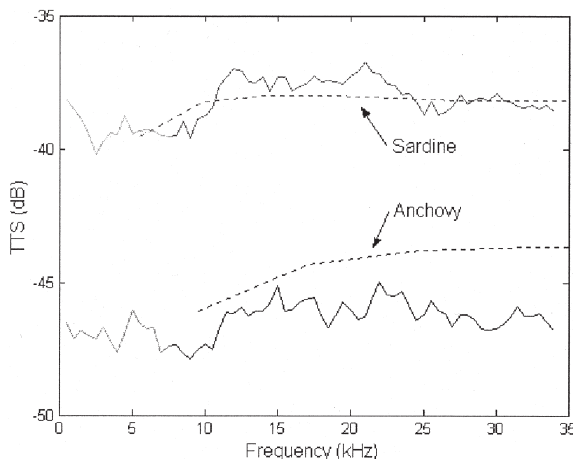


Figure 10. Average TTS measurement for the anchovy and the sardine for the low-frequency measurements (0.5–34 kHz). The dashed lines show the theoretical predictions for one anchovy and one sardine. The measurements below 5 and 7 kHz (grey) for the sardine and anchovy, respectively, are dubious because of the low number of modes excited in the cavity (see “Methods” section for elaboration).

The theoretical TTS predictions may be inaccurate for at least three reasons: first, the KRM accounts for only two diffractions in the body, whereas higher orders may be present and contribute appreciable effects (Foote, 1985); second, the KRM is not accurate for low values of kL (Medwin and Clay, 1998); and third, the swimbladder shape may not be well represented by the model parameters. For these reasons, significant discrepancies between the TTS measurements and the theoretical predictions at low kL were expected. However, at frequencies above 150 kHz, the differences between the KRM predictions and the TTS data for sardine were quite unexpected. The physical cause of this should be the subject of further investigation.

Conclusions

Using the method first described by De Rosny and Roux (2001) and the procedures described by Demer *et al.* (2003), the first measurements of total scatter have been made for anchovy (*Engraulis mordax*) and sardine (*Sardinops sagax caerulea*) over a wide bandwidth. These measurements demonstrate the feasibility of accurately estimating TTS(f) for fish moving in a highly echoic cavity. The ease with which TTS(f) measurements can be repeated with this technique provides unprecedented high precision for wide-bandwidth scattering measurements of moving fish. The resulting TTS(f) can be used to validate theoretical scattering models and improve the accuracy and precision of species classification and TS estimation

thereby reducing the uncertainty in the results of EI surveys of fish dispersion and abundance.

While the mean TTS(f) measurements were comparable to the KRM model predictions over a broad frequency band, there were some notable exceptions, viz. at the lowest frequencies the TTS(f) exhibited unpredicted plateaus from 7 to 25 kHz, and for sardine the TTS(f) decreased above 150 kHz at a rate proportional to f^3 .

Comparing the TTS(f) measurements for anchovy and sardine, the spectra are quite different. These differences, in both the mean amplitude and the spectral dynamics, may provide sufficient means for acoustically identifying these two species using wide-bandwidth or even multi-frequency echosounders. Providing that more accurate scattering models can be obtained for these species over this wide bandwidth, TTS(f) converted to the usual TS(f) may result in more accurate estimates of numerical fish densities when employing the EI method.

While a transformation of empirical TTS(f) to TS(f) is complicated, TTS(f) measurements can be used to validate scattering models that can be evaluated for TS(f). Typically, scattering models are validated at a single frequency and versus incidence angle. In contrast, TTS measurements, total scatter averaged over all incidence angles, can easily be obtained over a wide bandwidth. The latter is arguably a more robust way of testing the uncertainty of a scattering model, since highly accurate and precise measurements of TTS(f) are obtainable with the technique presented here.

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